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Mathur et al.

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(54) **TUNABLE FILTER WITH LEVERED MEMBRANE AND LONGER SCAN LENGTH**

(75) Inventors: **Vaibhav Mathur**, Arlington, MA (US); **Peter S. Whitney**, Lexington, MA (US); **James W. Getz**, Harvard, MA (US)

(73) Assignee: **Axsun Technologies, Inc.**, Billerica, MA (US)

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G02B 26/00 (2006.01)

(52) **U.S. Cl.**
CPC ***G02B 26/001*** (2013.01)

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USPC 359/577, 578, 291, 846, 847, 290, 223, 359/224, 900, 199.2, 200.6, 223.1
See application file for complete search history.

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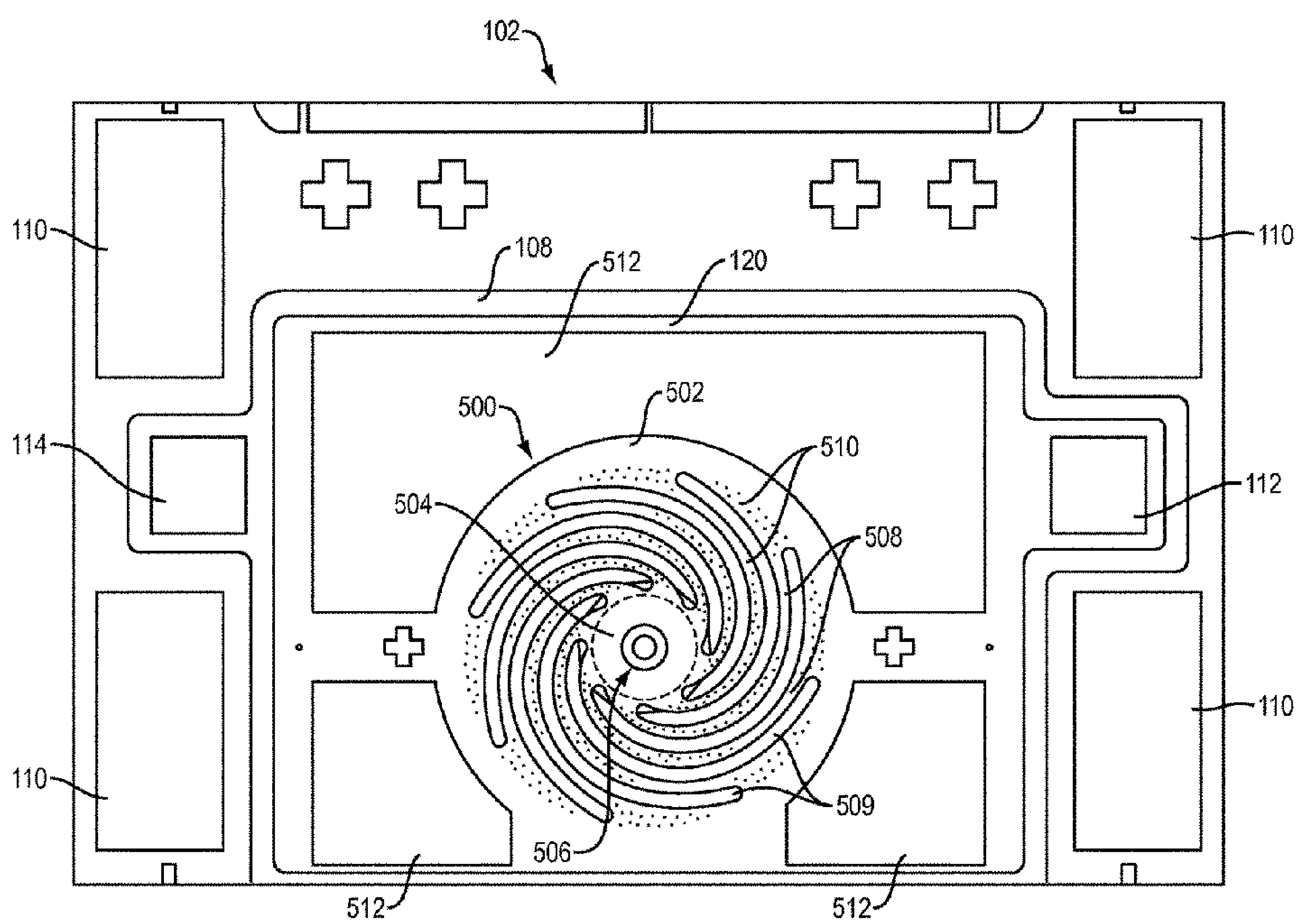
Primary Examiner — Thomas K Pham
Assistant Examiner — Sharrief Broome
(74) *Attorney, Agent, or Firm* — HoustonHogle LLP

(57) **ABSTRACT**

A Fabry-Perot tunable filter comprises a membrane device. The membrane device includes a support structure having an optical port. Also, the membrane device has an optical membrane structure separated from the support structure over the optical port. The optical membrane structure includes a center body portion and an outer body portion. Tethers extend radially from the center body portion to the outer body portion of the optical membrane structure. The center body portion has an area that is about equal or smaller than the area of the optical port.

25 Claims, 9 Drawing Sheets



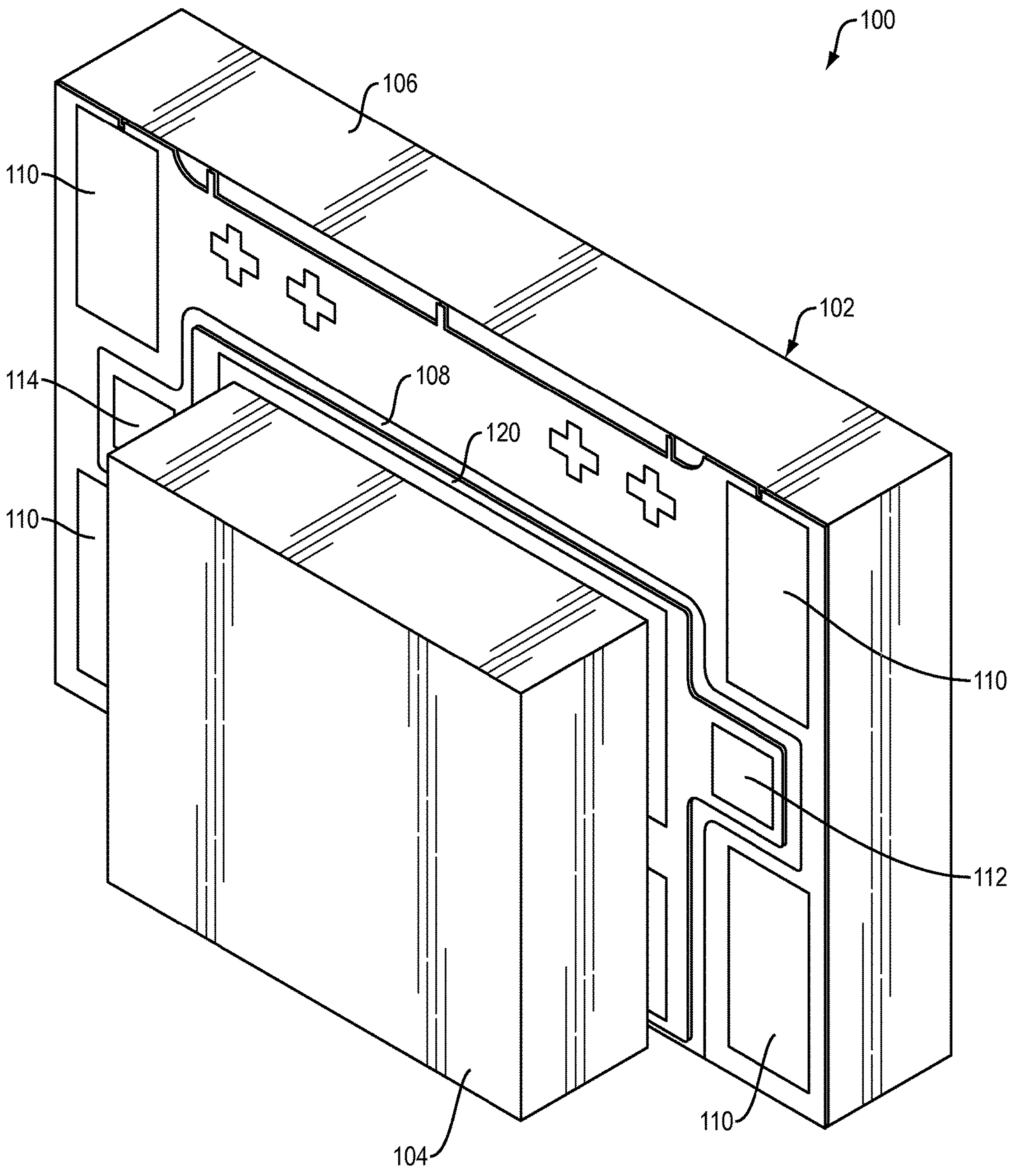


FIG. 1

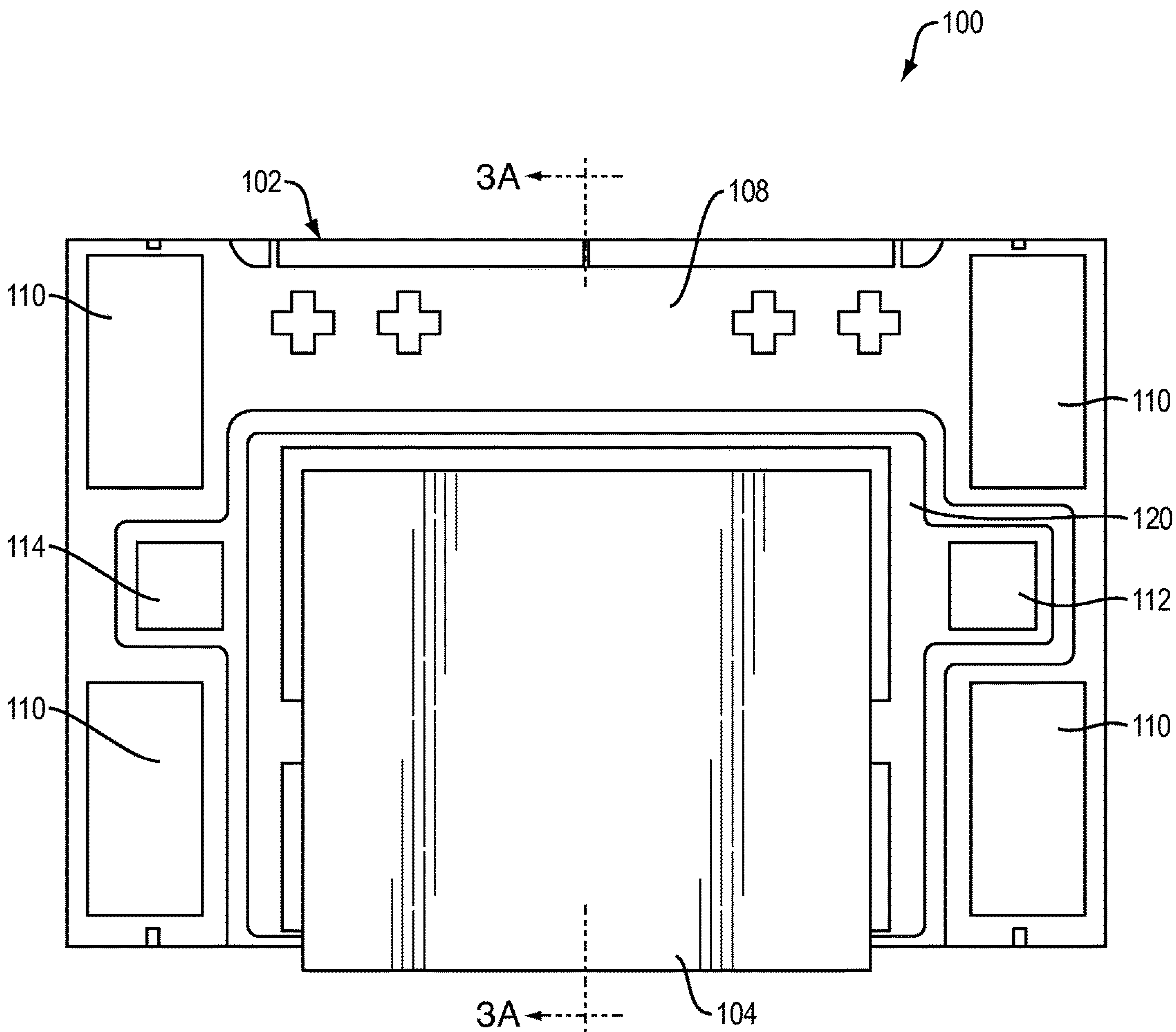


FIG. 2

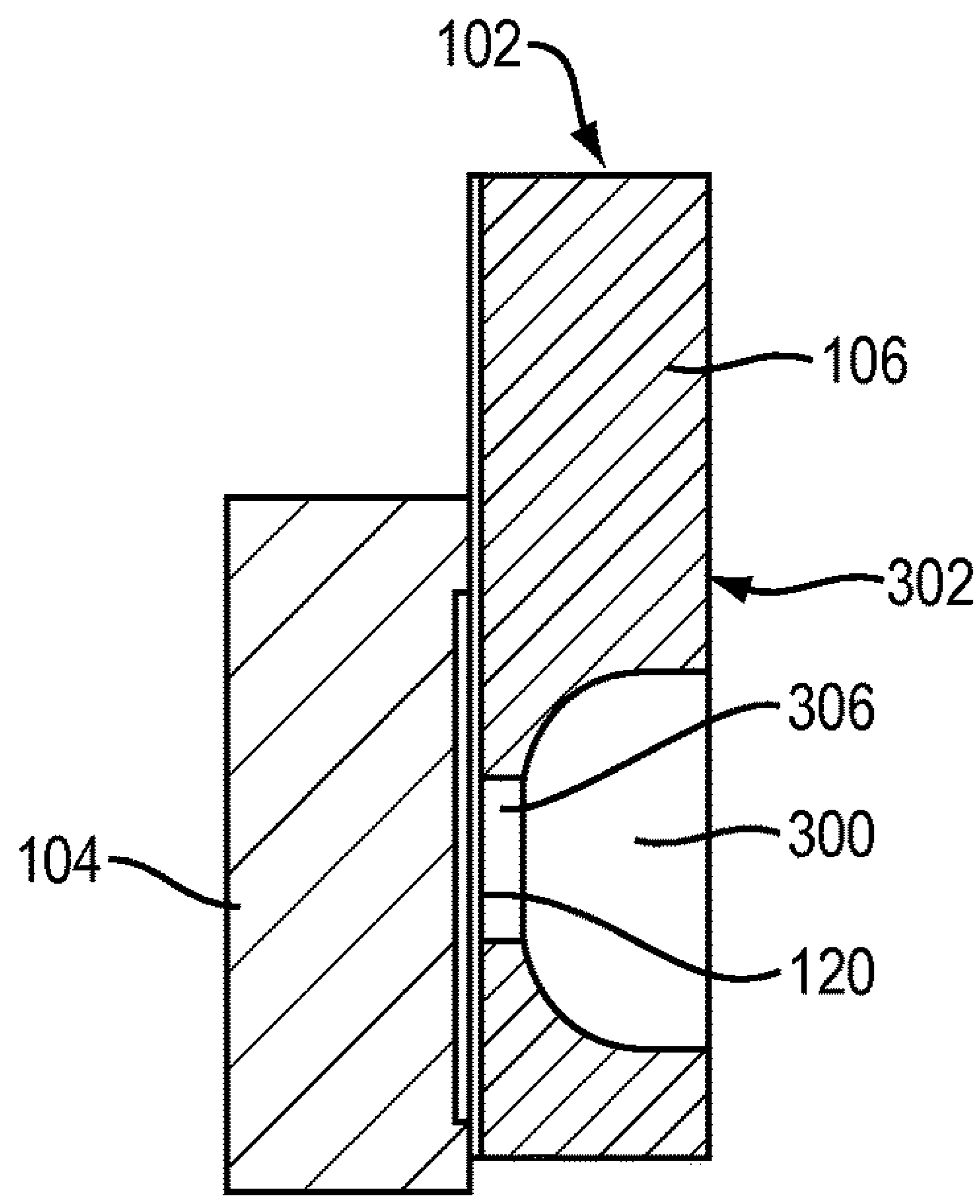


FIG. 3A

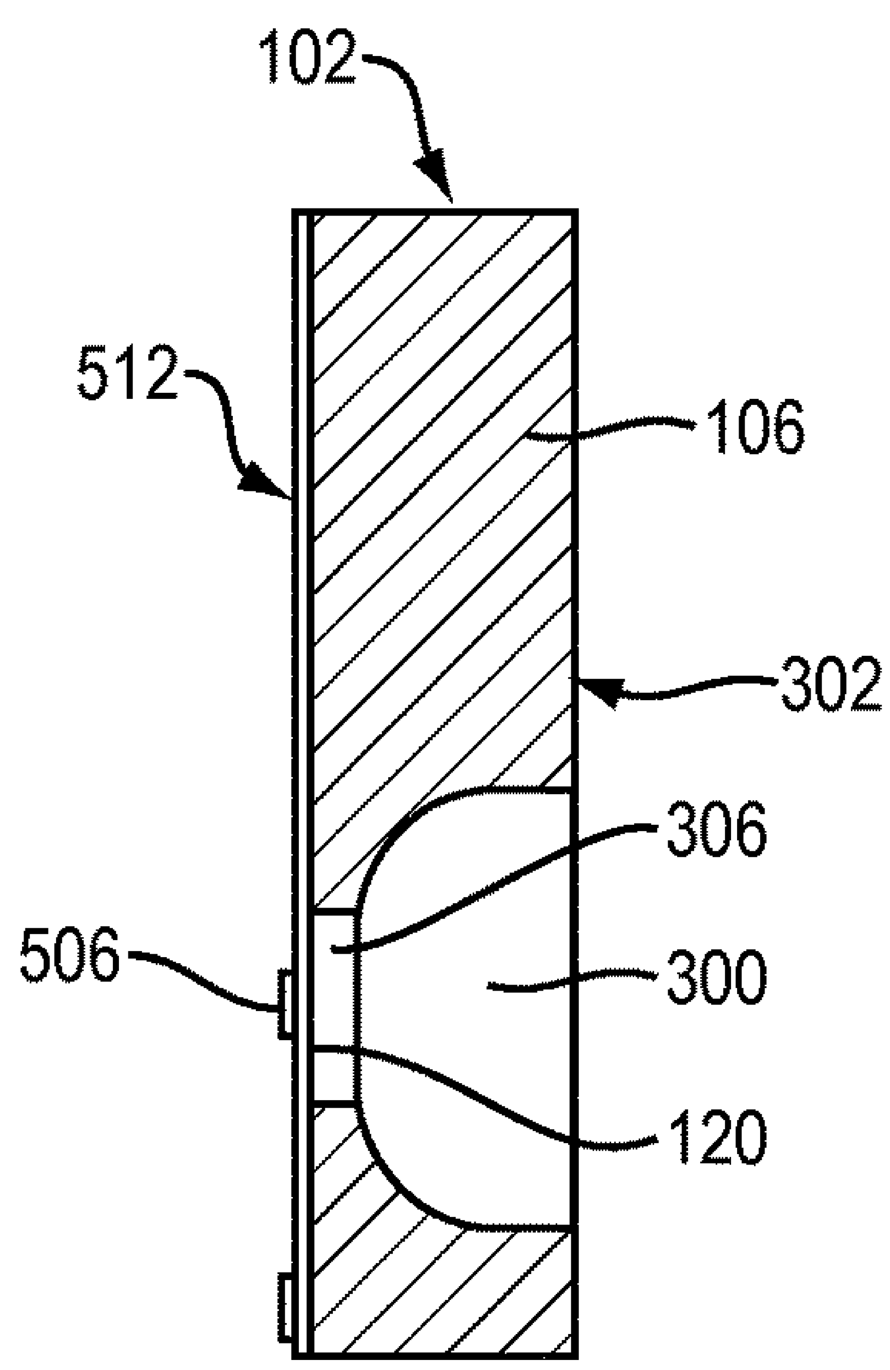


FIG. 3B

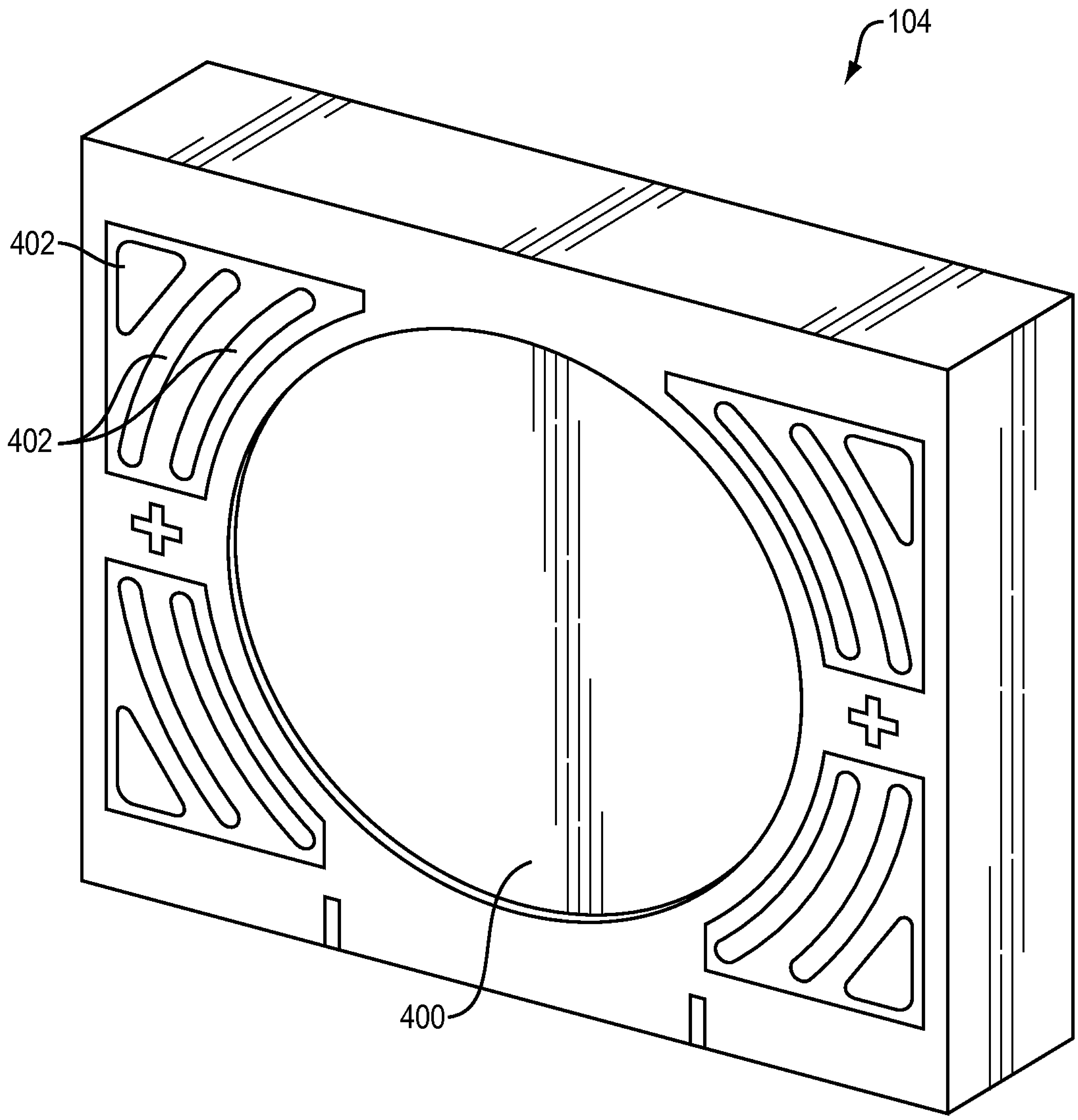


FIG. 4

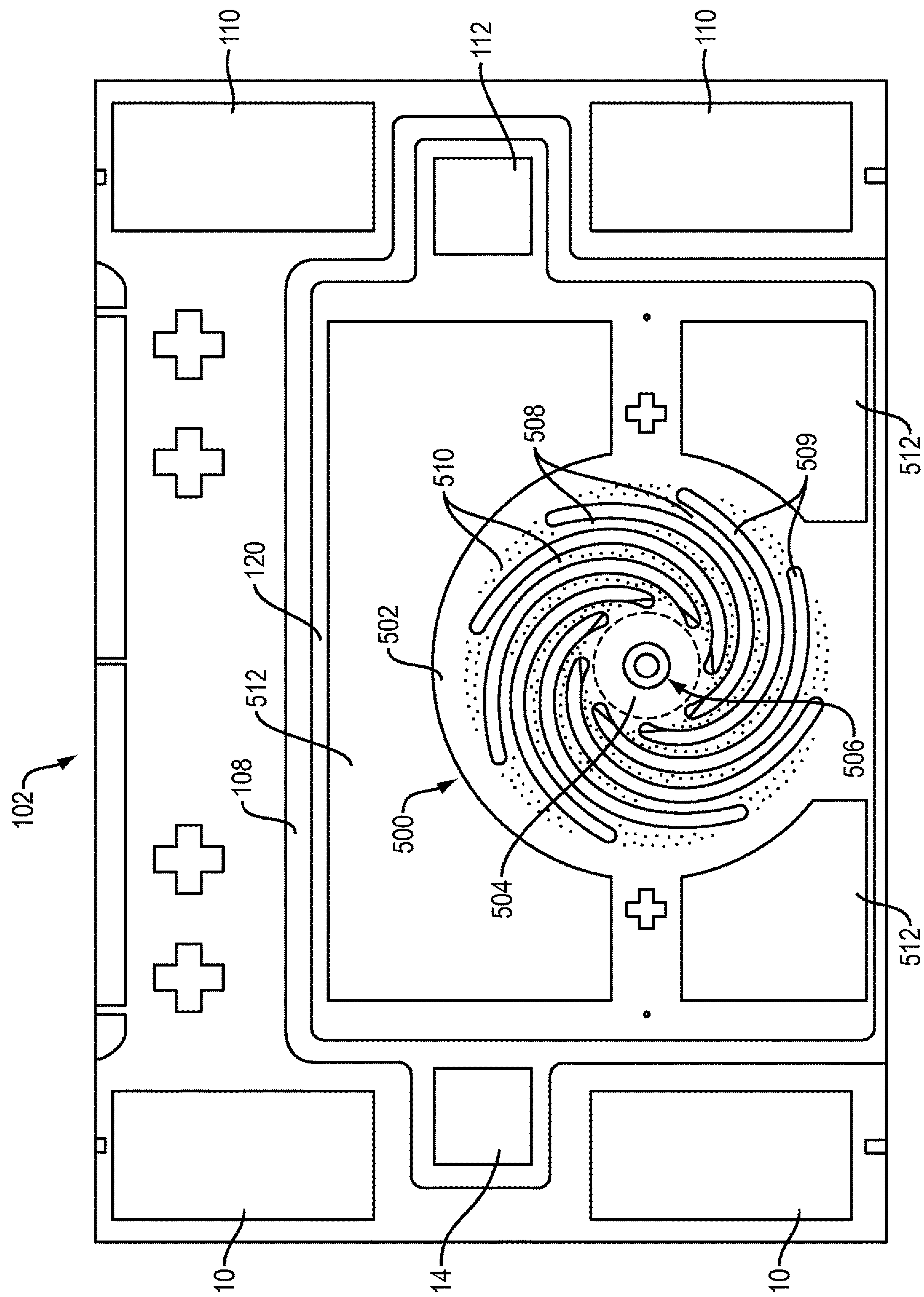

110
112
110
102
108
120
502
512
510
508
509
512
500
504
506
512
110
114
110

FIG. 5A

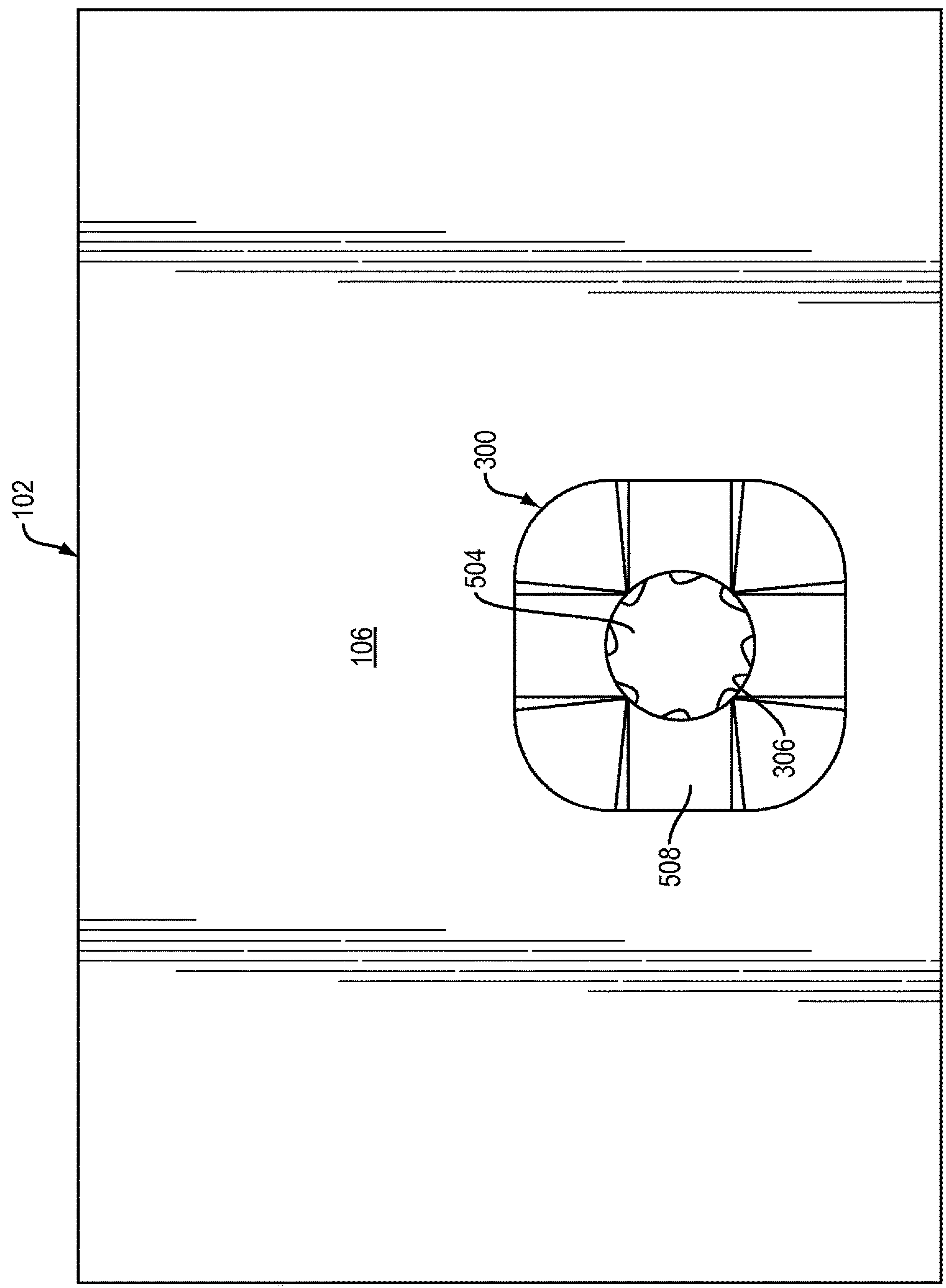


FIG. 5B

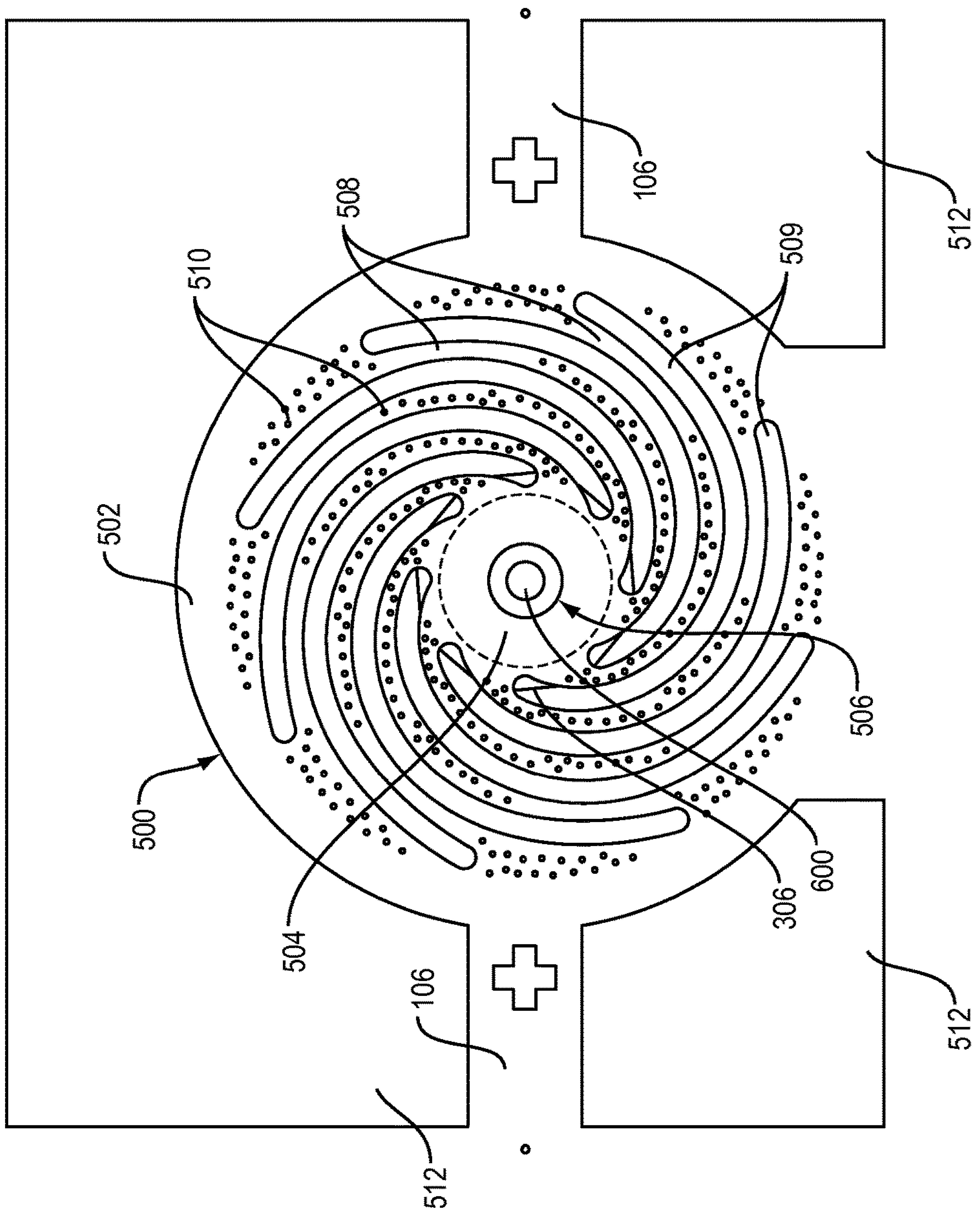


FIG. 6

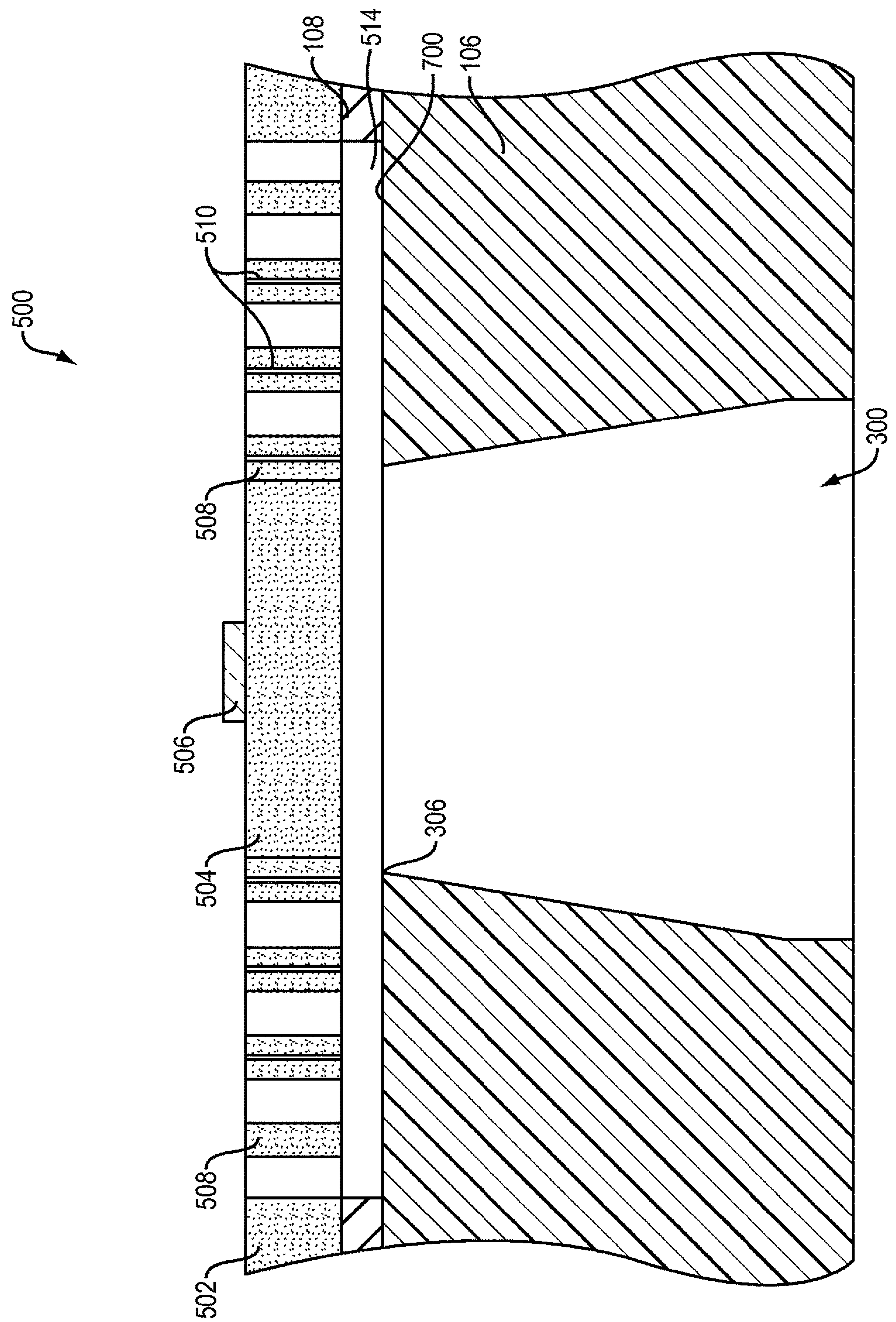


FIG. 7

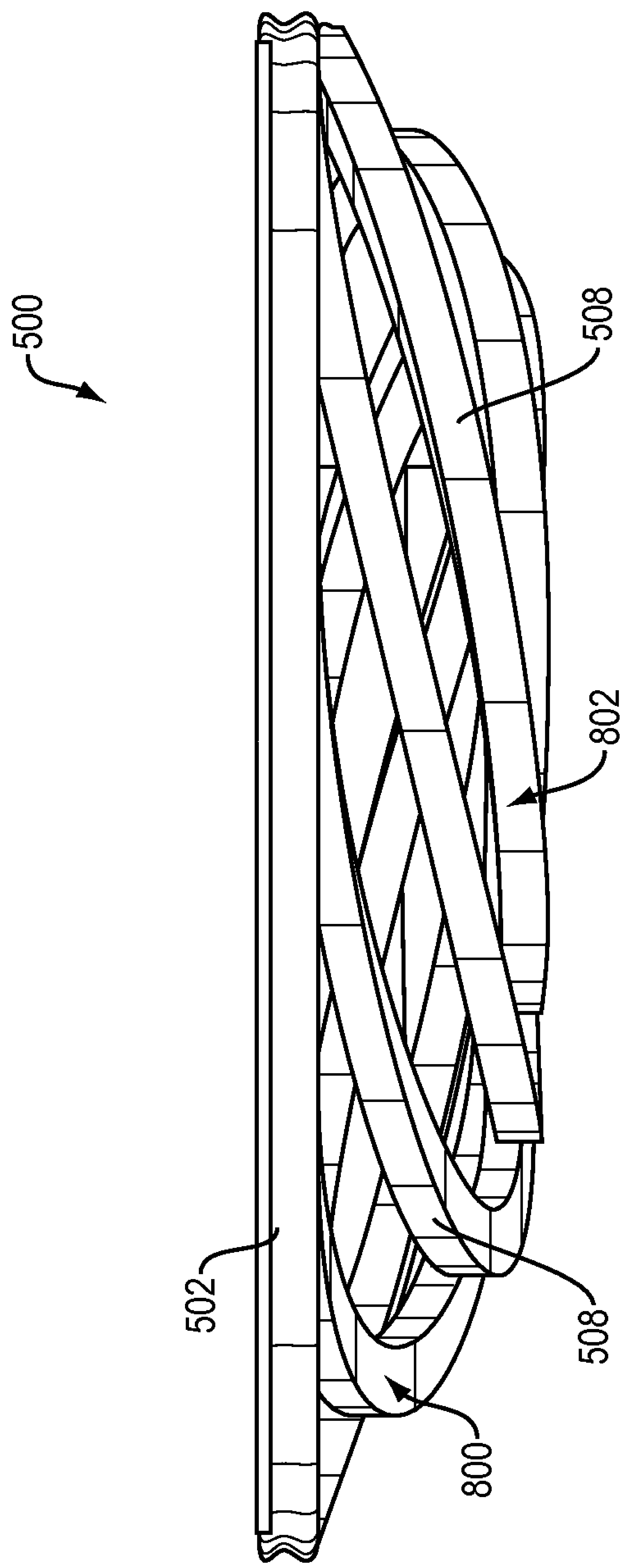


FIG. 8

TUNABLE FILTER WITH LEVERED MEMBRANE AND LONGER SCAN LENGTH

BACKGROUND OF THE INVENTION

MEMS or Micro Electro Mechanical Systems have become useful in a variety of fields. These MEMS have been applied to such technologies as inkjet printers, accelerometers, microphones, optical and electrical switching, and fluid acceleration. Over the last decade, there has been a focus towards the development of a subclass of these devices, termed Micro-Opto-Electro-Mechanical Systems (MOEMS).

One type of MOEMS device is an electrostatically deflectable membrane. Such MOEMS membranes are used in a variety of optical applications. For example, they can be coated to be reflective and then paired with a stationary mirror to form a tunable Fabry-Perot (FP) cavity/filter. They can also be used as stand-alone reflective components to define the end of a laser cavity, for example.

Typically, a voltage is applied between the membrane and an adjacent structure. When paired with a second fixed reflector, the FP cavity's separation distance changes through electrostatic attraction as a function of the applied voltage.

There are a few main components that typically makeup a MOEMS membrane device. In one example, the MOEMS membrane device includes a handle wafer support structure. An optical membrane layer is added to the handle wafer support structure; a deflectable membrane structure is then fabricated in this layer. This MOEMS membrane device includes an insulating layer separating the wafer support structure from the membrane layer. This insulating layer is partially etched away or otherwise removed to produce the suspended membrane structure in a release process. The insulating layer thickness defines an electrical cavity across which electrical fields are established that are used to electrostatically deflect the membrane structure.

One major problem with the many MOEMS membrane devices is "pull-in" instability. Pull-in voltage is understood as the voltage that results in an electrostatic force that causes a membrane structure to be pulled against a nearby surface. The instability arises when a membrane structure moves inward and the electrostatic forces overtake the mechanical restoring forces of the membrane structure. This can cause the membrane structure to snap-down uncontrollably into an adjacent surface such as the wafer support structure and sometimes even adhere to it through a process of stiction adhesion. Stiction is a strong attraction force that causes the adhesion of two elements to one another to the point of being almost unbreakable and results from Van der Waals forces, among others.

This problem can be especially intractable in the context of optical membrane structures of MOEMS devices. This is because anti-stiction coatings are typically incompatible with the required optical coatings, such as antireflective (AR) coatings or dielectric highly reflecting (HR) coatings, for example. Moreover, MOEMS membrane structures are typically especially smooth to maximize optical performance. The smoothness of the membrane typically increases the level of stiction forces in the event of contact.

There have been MOEMS membrane device designs that have tried to combat stiction adhesion. In one example, a MOEMS membrane device includes stiction plugs formed into the membrane structure and arranged so that the plugs project towards the adjacent support structure. Therefore, if the membrane comes in contact with the adjacent support structure, the stiction plugs first contact the adjacent surfaces preventing stiction adhesion of the membrane structure to the support structure.

SUMMARY OF THE INVENTION

The rule of thumb for electrostatic cavities is that the membrane structure should not be deflected greater than one-third the size of the electrostatic cavity to avoid snap-down. This limits the structure's tuning range. This problem can be addressed to some degree by increasing the size of the electrostatic cavity. However, a larger cavity by itself results in higher drive voltages. Thus, there is a need for a membrane design that allows for the membrane structure to move further downward while avoiding snap-down and higher drive voltages.

Also, there is a need for a much lower curvature sensitivity or variation of the membrane structure. Curvature sensitivity relates to the sensitivity of the membrane structure to external forces. For example, a membrane structure with high curvature sensitivity will easily become cupped in shape when forces pull on it inwards. Furthermore, a membrane structure with highly stressed coatings, for example, will bend into a concave or convex shape drastically affecting the device performance. Thus, it is desirable for the curvature sensitivity to be lowered so that the membrane structure can maintain a more flat surface.

In general, according to one aspect, the invention features a Fabry-Perot tunable filter comprising a membrane device. The membrane device includes a support structure having an optical port. Also, the membrane device has an optical membrane structure separated from the support structure over the optical port. The optical membrane structure includes a center body portion and an outer body portion. Tethers extend radially from the center body portion to the outer body portion of the optical membrane structure. The center body portion has an area that is about equal or smaller than the area of the optical port.

In embodiments, the optical port opening has a diameter between about 290 micrometers to about 400 micrometers and the center body portion has a diameter between about 300 micrometers to about 600 micrometers. Further, the optical membrane structure center body portion includes a membrane mirror that has a diameter between about 200 micrometers to about 250 micrometers.

Currently, the tethers form a spiral pattern around the center body portion of the optical membrane structure. An electrostatic driver is used to provide a voltage between the optical membrane structure and the support structure. This results in the deflection of the center body portion by a distance greater than ⅓ the distance to the support structure when driven by the electrostatic forces. Preferably, the center body portion deflects by about 50% the distance to the support structure, due to a levering effect since the electrostatic forces mainly work on the tethers and not the center body portion.

In the current embodiment, the insulating layer and thus the electrostatic cavity is between about 3 micrometers and about 6 micrometers in thickness.

The optical membrane structure and thus the membrane layer currently have a thickness of between about 5 micrometers and about 20 micrometers.

The above and other features of the invention including various novel details of construction and combinations of parts, and other advantages, will now be more particularly described with reference to the accompanying drawings and pointed out in the claims. It will be understood that the particular method and device embodying the invention are shown by way of illustration and not as a limitation of the invention. The principles and features of this invention may be employed in various and numerous embodiments without departing from the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

In the accompanying drawings, reference characters refer to the same or similar parts throughout the different views. The drawings are not necessarily to scale; emphasis has instead been placed upon illustrating the principles of the invention. Of the drawings:

FIG. **1** is a perspective view of a Fabry-Perot (FP) tunable filter comprising a mirror spacer bonded to an optical membrane device, according to an embodiment of the invention.

FIG. **2** is a front plan view of the FP tunable filter shown in FIG. **1**.

FIGS. **3**A-**3**B are cross-sectional views along cross-section A-A of FIG. **2** of the FP tunable filter with and without the mirror spacer, respectively, according to an embodiment of the invention.

FIG. **4** is a perspective view of the mirror spacer according to an embodiment of the invention.

FIG. **5**A is a front view of the optical membrane device according to an embodiment of the invention.

FIG. **5**B is a rear view showing the back-side of the optical membrane device and the optical port according to an embodiment of the invention.

FIG. **6** is a partial front view showing the details of the optical membrane structure according to an embodiment of the invention.

FIG. **7** is a schematic cross-section view of the optical membrane device according to an embodiment of the invention.

FIG. **8** is a perspective view showing the deflection of the optical membrane structure according to an embodiment of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. **1** shows a MEMS Fabry-Perot (FP) tunable filter **100** that has been constructed according to the principles of the present invention.

The FP tunable filter **100** comprises a mirror spacer **104** coupled to an optical membrane device **102** forming one unit.

The membrane device **102** includes a support structure **106**. The support structure **106** functions as a base for the other components of the membrane device **102**.

In one example, the support structure **106** can be made from a wafer material or more specifically a handle wafer material. The handle wafer material is from a silicon wafer that is singulated to form the support structure in FIG. **1**.

The membrane device **102** further includes an insulating layer **108**. The insulating layer **108** is positioned over the support structure **106**. A membrane layer **120** is provided on the insulating layer **108**. The insulating layer **108** functions as a sacrificial/release layer for the membrane structure that is formed in the membrane layer **120**. In one example, the insulating layer is between about 3 and 6 micrometers in thickness.

In this example, there are four metal pads **110** positioned at each corner of the membrane device **102**. These metal pads **110** are useful for installing the filter **100** on a micro-optical bench or clip or LIGA structures, for example.

Also, there are two wire metal bond pads **112**/**114** further provided on the front of the membrane device **102** and positioned vertically between two of the metal pads **110** on opposite lateral sides of the membrane device **102**. Membrane layer wire bond pad **112** provides electrical access for electrical control of the membrane layer **120**. The other wire bond pad is a support structure bond pad **114** that provides electrical access to the support structure **106**.

FIG. **2** is a front view of the tunable filter **100** shown in FIG. **1**. The spacer **104** fits and attaches directly into a middle section of the membrane device **102** to form a unit that can be used as a FP tunable filter **100**.

In FIGS. **3**A-**3**B, the cross-section of the FP tunable filter **100** is viewed along line A-A of FIG. **2** with and without the spacer **104**. An optical port **300** is shown along the cross-section within the membrane device **102**. The optical port **300** extends entirely through from the distal side **302** of the support structure **106** to expose the backside of the membrane layer **120**.

FIG. **3**A shows the optical membrane device **102** with the mirror spacer **104** attached. The mirror spacer **104** is attached or bonded directly over the optical port opening **306**.

FIG. **3**B shows the optical membrane device **102** without the mirror spacer. The solder bond pads **512** enable attachment of the mirror spacer **104** to the optical membrane device **102**. A highly reflecting mirror **506** is deposited on the center of the membrane structure.

FIG. **4** is a front view of the mirror spacer **104**. A circular mirror **400** is recessed into the center of the mirror spacer **104**. The mirror **400** is formed by depositing a high reflectivity (HR) coating such as a dielectric mirror coating or reflective metal coating in the recess. When attached to the membrane device **102**, the mirror spacer **104** functions to separate the mirror **400** from the membrane structure to thereby define a FP cavity. The mirror spacer **104** also includes pre-deposited solder pads **402** set at each corner of the mirror spacer **104** surrounding the mirror **400**. The pre-deposited solder **402** allows for the mirror spacer **104** to be bonded onto the metal or solder pads **512** of the membrane device **102**.

FIGS. **5**A and **5**B are front and back views of the optical membrane device **102**.

FIG. **5**A is a front view of the optical membrane device **102** without the mirror spacer **104**.

As described above, the mirror spacer **104** is attached to the front of the optical membrane device **102**. More specifically, the mirror spacer **104** is attached onto the membrane device **102** so that the mirror **400** is affixed over an optical membrane structure **500** using metal pads **512**.

The optical membrane structure **500** is fabricated in the optical membrane layer **120** that was formed on or attached to the insulating layer **108**. In one example, the optical membrane structure **500** has an overall circular shape formed within the membrane layer **120**.

The optical membrane structure **500** can be made from silicon. For example, the optical membrane layer can be manufactured from a silicon wafer that has been bonded to the insulating layer **108** under elevated heat and pressure. Other alternatives are, however, silicon nitride, polycrystalline silicon, or essentially single crystal silicon, which have been deposited on the insulating layer **108**.

The optical membrane structure **500** is layered or installed on the sacrificial insulating layer **108**. The insulating layer

108 functions as a sacrificial/release layer, which is partially removed to release the optical membrane structure **500** from the support structure **106**.

In one example, the optical membrane structure **500** is about 5 to 20 micrometers in thickness or more preferably about 5 to 10 micrometers in thickness. Such thickness range provides adequate structural integrally while not making the structure overly rigid or brittle.

The optical membrane structure **500** includes an outer body portion **502** and a center body portion **504**. The outer body portion **502** is an outer edge of the optical membrane structure **500**. The center body portion **504** is the central section of the optical membrane structure **500** that is supported over the optical port **300**. In one example, the center body potion **504** is between about 300 and 600 micrometers in diameter.

The center body portion **504** includes a membrane mirror **506**. The membrane mirror **506** is directly in the middle of the optical membrane structure **500**. The membrane mirror **506** has a diameter between about 200 micrometers to about 250 micrometers. Also, in one example, the membrane mirror **506** is made from a dielectric mirror coating that is deposited on the membrane layer **120**.

The optical membrane structure **500** includes tethers **508** that extend radially from the outer body portion **502** to the center body portion **504** in a spiral pattern such that each tether extends through greater than a 90 degree arc. In the illustrated example, there are 8 tethers **508**. In general, the number of tethers is typically between 4 and 20. The outer body portion **502** forms a ring where the tethers **508** terminate. The tethers **508** are defined by cuts **509** or slots formed around the center body portion **504** within the optical membrane layer **120**.

The tethers **508** include holes **510** scattered across each tether **508** from the outer body portion **502** to the center body portion **504**. These holes **510** are etchant holes that allow etchant to pass through the optical membrane structure **500** to assist in the removal of the insulating layer **108** during the release process.

Also, FIG. **5**A shows the three metal bond pads **512** positioned around the optical membrane structure **500**. These metal bond pads **512** are deposited on the proximal side of the optical membrane structure **500**. The metal bond pads **512** are used to solder bond, for example, the mirror spacer **104** to the optical membrane device **102**. In an alternative example, the mirror spacer **104** can be integral with the optical membrane device **102**.

FIG. **5**B is a backside view of the optical membrane device **102**. An optical port **300** is formed through the support structure **106** of the optical membrane device **102**. This is for enabling optical access to the optical membrane structure **500** from the bottom or backside of the optical membrane device **102**. As a result, looking through the backside of the optical membrane device **102**, the center body portion **504** and tethers **508** of the optical membrane structure **500** can be observed.

In one example, the optical port **300** has inward sloping sidewalls **508** that end in the port opening **306**. In a further example, the optical port opening **306** has a diameter between about 290 micrometers to about 400 micrometers.

FIG. **6** is a zoomed-in front view of the optical membrane structure **500**.

The optical membrane structure **500** is supported over the optical port **300** with support from the support structure **106** and insulating layer **108** of the optical membrane structure **500**.

As discussed above, the optical membrane structure **500** includes tethers **508** extending from the outer body portion **502** to the center body portion **504** of the optical membrane structure **500**. In one example, the tethers **508** form a spiral pattern around the center body portion **504**. In another example, the tethers can have a length of about 470 micrometers. Also, the tethers can have a thickness between about 5 to 20 micrometers or more preferably about 5 to 10 micrometers in thickness.

The area or diameter of the center body portion **504** is about equal or smaller than the area of the optical port opening **306**. In general, the diameter of the center body portion **504** is about 120% of the diameter of the optical port opening **306** or less. Preferably, the center body portion **504** has a diameter that is less than the optical port opening **306**. In the FIG. **6** example, the center body portion **504** is smaller in diameter than that of the optical port opening **306** by 10% or more. This relationship is important for allowing the center body portion **504** to increase its downward deflection distance with respect to the optical port **300** while still combating pull-in instability forces. In the current embodiment, the center body **504** is capable of deflecting more than a ⅓ of the electrostatic gap, up to 50% of the electrostatic gap or more because of a levering effect.

In one embodiment, the membrane mirror **506** has an optically curved surface **600**. This optical surface **600** is formed centrally on the membrane mirror **506**. In one example, the surface **600** is fabricated as described in U.S. Pat. No. 7,416,674. The curvature of the surface is designed as described in U.S. Pat. No. 6,810,062 in order to suppress higher order modes within the filter cavity. In another example, the area of the membrane mirror **506** is between about 39% to about 48% of the area of the optical port opening **306**.

In the implementation as a Fabry-Perot filter or other reflecting membrane, the optical coating dot **506** is preferably a highly reflecting (HR) dielectric mirror stack. This yields a highly reflecting, but low absorption, structure that is desirable in, for example, the manufacture of high finesse Fabry-Perot filters.

FIG. **7** is a schematic cross-section of the optical membrane structure **500** supported above the optical port opening **306**.

The optical port **300** is formed through the support structure **106**. As described above, the walls of the optical port **300** slope inward and terminate at the optical port opening **306** to define the extent of an electrostatic cavity in region **514**. This electrostatic cavity region **514** was formed by the removal of the insulating layer **108**.

The support structure **106** supports the remaining insulating layer **108** surrounding the optical port **300**. The outer body portion **502** of the membrane layer **120** is configured over the insulating layer **108**.

An external electrostatic driver provides a voltage between the optical membrane structure **500** and the support structure **106**. This causes the center body portion **504** to move downwards towards the port opening **700** of the optical port **300**. Thus, the size of the FP cavity can be modulated by establishing an electrostatic drive voltage.

As shown in FIG. **7**, the spiral tethers **508** extend from the outer body portion **502** to the center body portion **504** close to where the optical port opening **306** begins. The center body **504** is supported by the tethers **508** over the optical port opening **306**. As the center body **504** moves downwards into the port opening **700**, the tethers **508** flex or extend to a point while still restricting the center body **504** from moving far enough down to enable pull-in instability and the consequence of stiction to occur.

FIG. **8** shows the deflection of the optical membrane structure **500**. The deflection of an optical membrane structure **500** in terms of distance is in the range of micrometers. Thus, FIG. **8** is a magnified view with respect to actual deflection.

The optical membrane structure **500** can only be deflected across approximately one-third of the electrostatic cavity length that is defined by the thickness of the insulating layer **108**. Larger deflections can result in snap down, where the optical membrane structure **500** moves in an uncontrolled fashion to contact a stationary electrostatic electrode or nearby surface.

In the present design, the electrostatic cavity **514** is located entirely or largely underneath the tethers **508**. In the illustrated example, the optical port opening **306** generally circumscribes the center body portion **504** of the membrane structure **500**. Therefore, the tethers on average can only deflect about one third of the size of the electrostatic cavity **514**. However, the center body portion **504** can actually deflect more than this one third distance because of the lever effect. This is because the electrostatic cavity operates mainly on the tethers **508** rather than the tethers **508** and the center body portion **504**. Thus, with the present design, the center body portion **504** can deflect more than would typically be associated with the electrostatic cavity.

In one example, as the center body portion **504** of the optical membrane structure **500** moves downward due to application of a voltage, the tethers **508** also move downwards to compensate for the center body portion **504** movement. The tethers **508** extend in varying degrees from the outer body portion **502** to the center body portion **504**. The distal sections **800** of the tethers **508**, with respect to the center body portion **504**, deflect the least distance while the proximal sections **802** of the tethers **508**, with respect to the center body portion **504**, deflect the longest distance.

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.

What is claimed is:

1. A Fabry-Perot tunable filter comprising:

a membrane device comprising:

a support structure having an optical port opening;

an optical membrane structure separated from the support structure over the optical port, wherein the optical membrane structure includes a center body portion, an outer body portion, and tethers extending radially from the center body portion to the outer body portion of the optical membrane structure, wherein a diameter of the center body portion is smaller than a diameter of the optical port opening with inner end portions of the tethers being visible from a backside of the optical membrane structure through the optical port;

wherein the center body portion deflects greater ⅓ the distance to the support structure when driven by electrostatic forces.

2. The Fabry-Perot tunable filter of claim **1** wherein the optical port opening has a diameter between about 290 micrometers to about 400 micrometers.

3. The Fabry-Perot tunable filter of claim **1** wherein the center body portion has a diameter between about 300 micrometers to about 600 micrometers.

4. The Fabry-Perot tunable filter of claim **1** wherein the optical membrane structure center body portion includes a membrane mirror.

5. The Fabry-Perot tunable filter of claim **4** wherein the membrane mirror has a diameter between about 200 micrometers to about 250 micrometers.

6. The Fabry-Perot tunable filter of claim **4** wherein the membrane mirror is coated with an optical coating dot.

7. The Fabry-Perot tunable filter of claim **6** wherein the optical coating dot is a highly reflecting dielectric mirror stack.

8. The Fabry-Perot tunable filter of claim **1** wherein the tethers form a spiral pattern around the center body portion of the optical membrane structure.

9. The Fabry-Perot tunable filter of claim **1**, further comprising a mirror spacer attached over a front side of the membrane device.

10. The Fabry-Perot tunable filter of claim **9** wherein the mirror spacer includes a circular mirror recessed into the mirror spacer.

11. The Fabry-Perot tunable filter of claim **10** wherein the mirror is formed from a high reflectivity coating.

12. The Fabry-Perot tunable filter of claim **1**, further comprising an electrostatic driver for providing a voltage between the optical membrane structure and the support structure.

13. The Fabry-Perot tunable filter of claim **1** wherein the support structure is a wafer material.

14. The Fabry-Perot tunable filter of claim **13** wherein the wafer is singulated to form the support structure.

15. The Fabry-Perot tunable filter of claim **1** wherein the tethers include holes formed along each tether.

16. The Fabry-Perot tunable filter of claim **1** wherein the optical membrane device further comprises an insulating layer separating the optical membrane structure from the support structure.

17. The Fabry-Perot tunable filter of claim **16** wherein the insulating layer is between about 3 micrometers and about 6 micrometers in thickness.

18. The Fabry-Perot tunable filter of claim **16** wherein the optical membrane device further comprises a membrane layer wire bond pad deposited on the insulating layer.

19. The Fabry-Perot tunable filter of claim **16** wherein the optical membrane device further comprises a support structure bond pad deposited on the insulating layer.

20. The Fabry-Perot tunable filter of claim **1** wherein the optical membrane structure has a thickness between about 5 micrometers and about 20 micrometers.

21. The Fabry-Perot tunable filter of claim **1** wherein the center body portion deflects more than 50% the distance to the support structure when driven by electrostatic forces.

22. A membrane device comprising:

a support structure having an optical port opening;

an optical membrane structure separated from the support structure over the optical port, wherein the optical membrane structure includes a center body portion, an outer body portion, and tethers extending radially from the center body portion to the outer body portion of the optical membrane structure, wherein the tethers are electrostatically deflected over about one-third of a distance to the support structure and the center body portion deflects by more than 50% of the distance.

23. The device as claimed in claim **22** wherein the center body portion is smaller in diameter than the optical port opening by 10% or more.

24. A Fabry-Perot tunable filter comprising:

a membrane device comprising:

a support structure having an optical port opening;

an optical membrane structure separated from the support structure over the optical port, wherein the optical membrane structure includes a center body portion, an outer body portion, and tethers extending radially from the center body portion to the outer body portion of the optical membrane structure, wherein a diameter of the center body portion is smaller than a diameter of the optical port opening with inner end portions of the tethers being visible from a backside of the optical membrane structure through the optical port;

wherein the center body portion is smaller in diameter than the optical port opening by 10% or more.

25. The device as claimed in claim **22** wherein inner end portions of the tethers are visible from a backside of the optical membrane structure through the optical port.

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